Evaluation of Liquefaction Potential Index (LPI) for Assessing Liquefaction Hazard: A Case Study in Christchurch, New Zealand

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BACKGROUND

- Soil liquefaction is responsible for tremendous damage to civil infrastructure. Its effects were vividly displayed during the 2010-2011 Canterbury, New Zealand earthquake sequence, which caused widespread and severe liquefaction throughout the city of Christchurch.

Fig 1. Liquefaction effects during the Canterbury, New Zealand earthquake sequence

- Liquefaction "triggering" procedures predict whether soil at a specific depth will liquefy, but they do not predict the severity of liquefaction manifestation at the ground surface, which more directly correlates to damage potential and the cumulative response of the soil deposit.
- To fill this gap, Iwasaki et al. (1978) proposed the liquefaction potential index (LPI) to assess the damage potential of liquefaction, where LPI is computed as:

$$\mathrm{LPI} = \int_0^{20\,\mathrm{m}} \mathrm{F} \cdot \mathrm{w(z)}\,\mathrm{dz}$$

where: $\mathrm{w(z)} = 10 - 0.5\mathrm{z}$ (depth weighting factor)

$$\mathrm{F} = 1 - \mathrm{FS}_{liq} \quad \text{for } \mathrm{FS}_{liq} \le 1$$
$$\mathrm{F} = 0 \quad \text{for } \mathrm{FS}_{liq} > 1$$

- Iwasaki et al. proposed that severe liquefaction should be expected if **LPI > 15** but not if **LPI < 5**. This criterion for liquefaction manifestations, defined by two threshold values of LPI, is referred to as the *Iwasaki criterion*.
- LPI has been used to characterize liquefaction hazards worldwide, but existing **calibrations** of LPI to observed liquefaction severity **are limited,** are based on generally **modest datasets**, and propose a **wide range** of suggested LPI threshold values:

Table 1. Existing Assessments of LPI

Study	Threshold LPI Value For:	
	Liquefaction	Severe Liquefaction
Iwasaki et al. (1978)	5	15
Lee et al. (2003)	13	21
Toprak & Holzer (2003)	5	15
Papathanassiou (2008)	19	32

- Thus, the **efficacy** of the LPI framework and **accuracy** of derivative liquefaction hazard maps developed for regions around the world are **highly uncertain**.

OBJECTIVE

- **Utilizing CPT soundings from nearly 1200 sites, each with field observations during both the Darfield and Christchurch earthquakes, this study aims to evaluate the performance of LPI in predicting the occurrence and severity of surficial liquefaction manifestations.**
- It is hypothesized that this study will resolve the accuracy of existing hazard maps and identify mechanisms for improving LPI predictions by providing the most extensive field evaluation of LPI performance to-date.

DATA AND METHODOLOGY

Facilitated by records from a dense network of strong-motion stations, extensive in-situ soil characterization data, and detailed documentation of liquefaction severity, the Canterbury earthquakes present a truly unique opportunity to improve our understanding of liquefaction hazards.

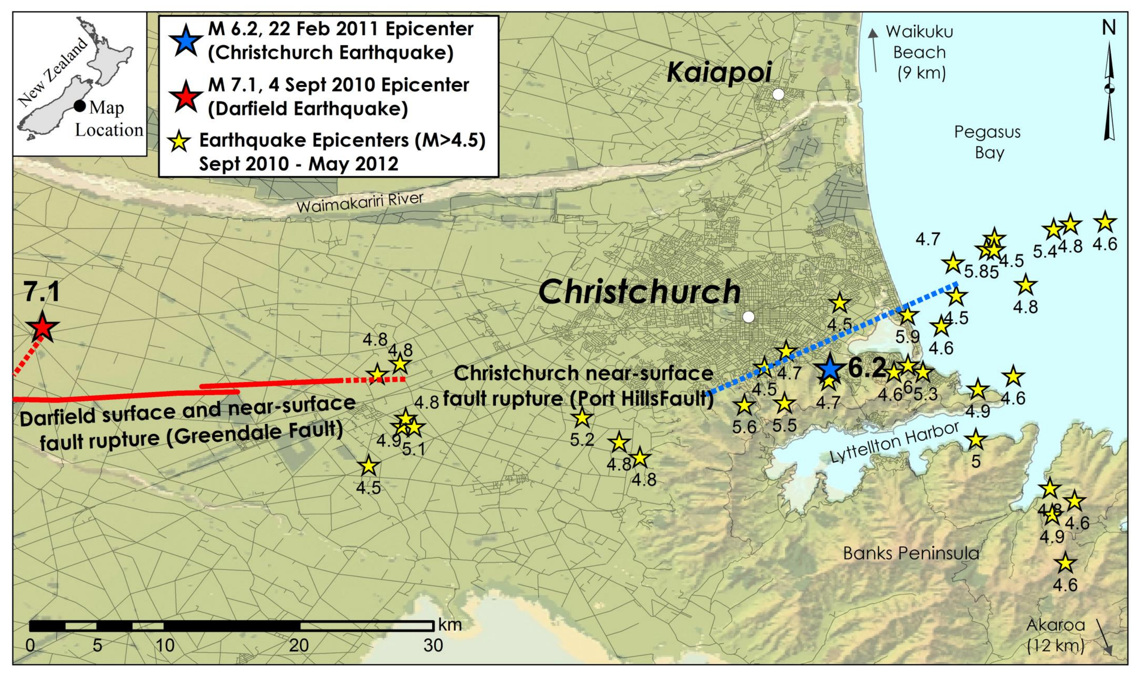

Fig 2. Overview of Canterbury earthquake sequence

1. Canterbury Earthquake Sequence

- 4 Sept 2010 M_w7.1 Darfield earthquake
- 22 Feb 2011 M_w6.2 Christchurch earthquake
- 11 other $M_w \ge 5.0$ events

2. CPT Soundings

- 1495 CPT soundings performed in Christchurch region
- Anselin Local Morans I analysis used to remove 322 soundings prematurely terminating on shallow gravels

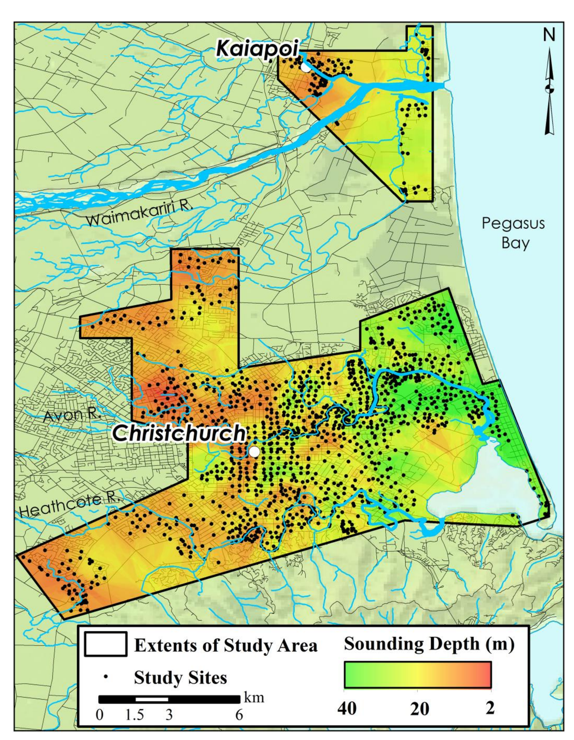

Fig 3. CPT sounding depths

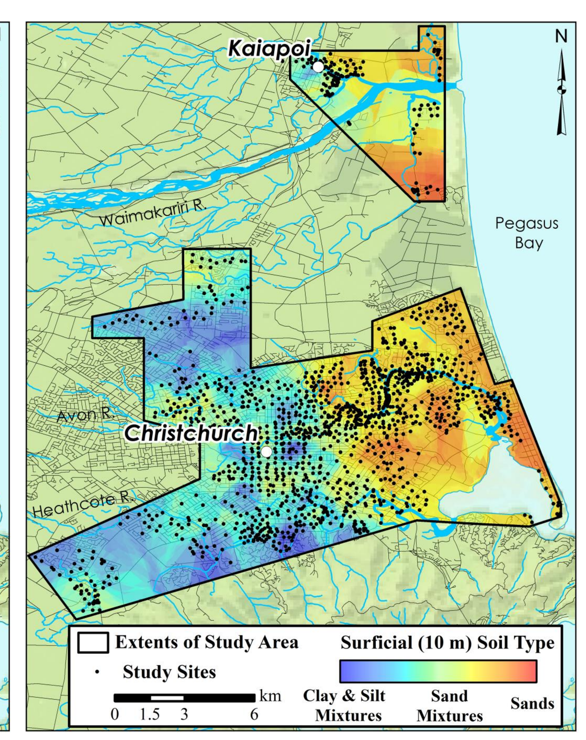

Fig 4. Surficial soil type

3. Liquefaction Severity

- Characterized at each CPT site following both the Darfield and Christchurch earthquakes using ground reconnaissance, high-resolution satellite imagery, and lateral spread measurements.

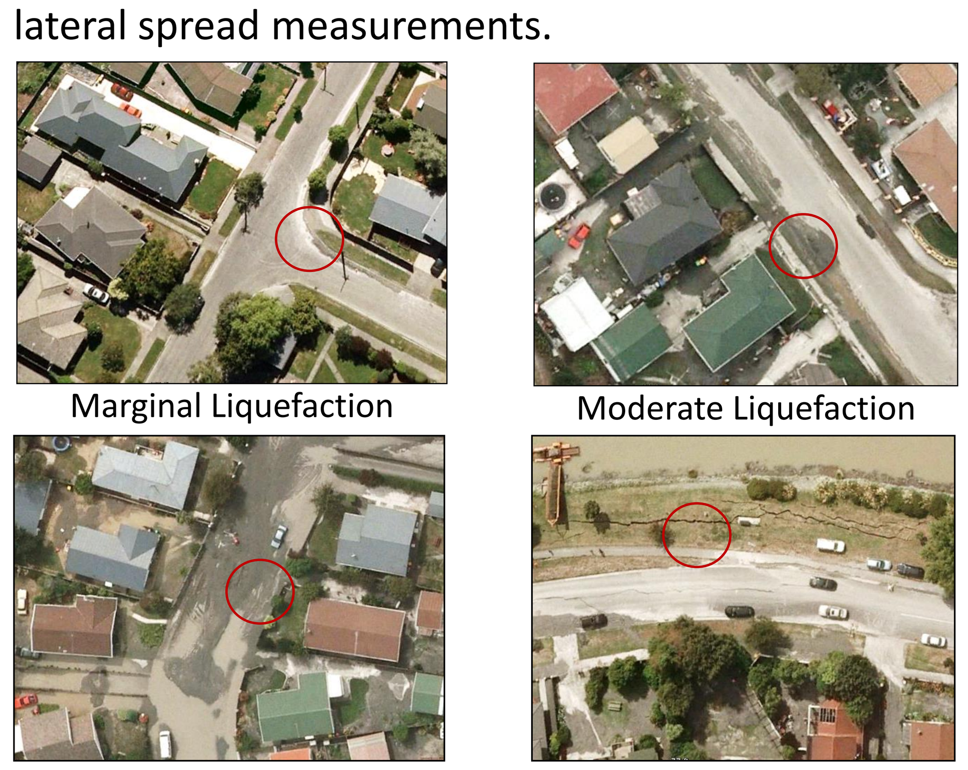

Fig 5. Representative liquefaction observations

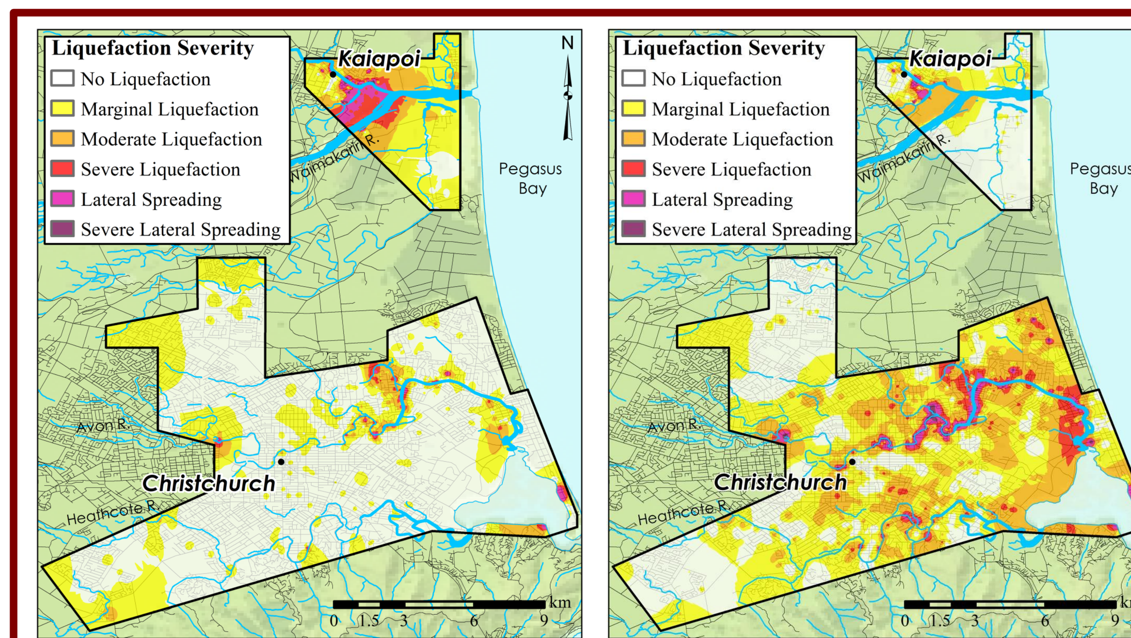

Fig 6. Liquefaction severity during the (a) Darfield and (b) Christchurch earthquake

4. Conditional Peak Ground Accelerations (PGAs)

- Using more than 20 near-source strong-motion station recordings, the Bradley (2010) GMPE, and the spatial correlation model of Goda & Hong (2008), conditional PGA distributions were computed from:

$$[\ln \mathrm{PGA}_{site} \mid \ln \mathrm{PGA}_{SMstation}] = N(\ln \overline{\mathrm{PGA}_{site}} + \eta + \mu_{\varepsilon_{site}|\varepsilon_{SMstation}}, \sigma^2_{\varepsilon_{site}|\varepsilon_{SMstation}})$$

5. Liquefaction Evaluation and LPI

- FS_{liq} computed from Robertson and Wride (1998)
- LPI computed as per Iwasaki et al. (1978)

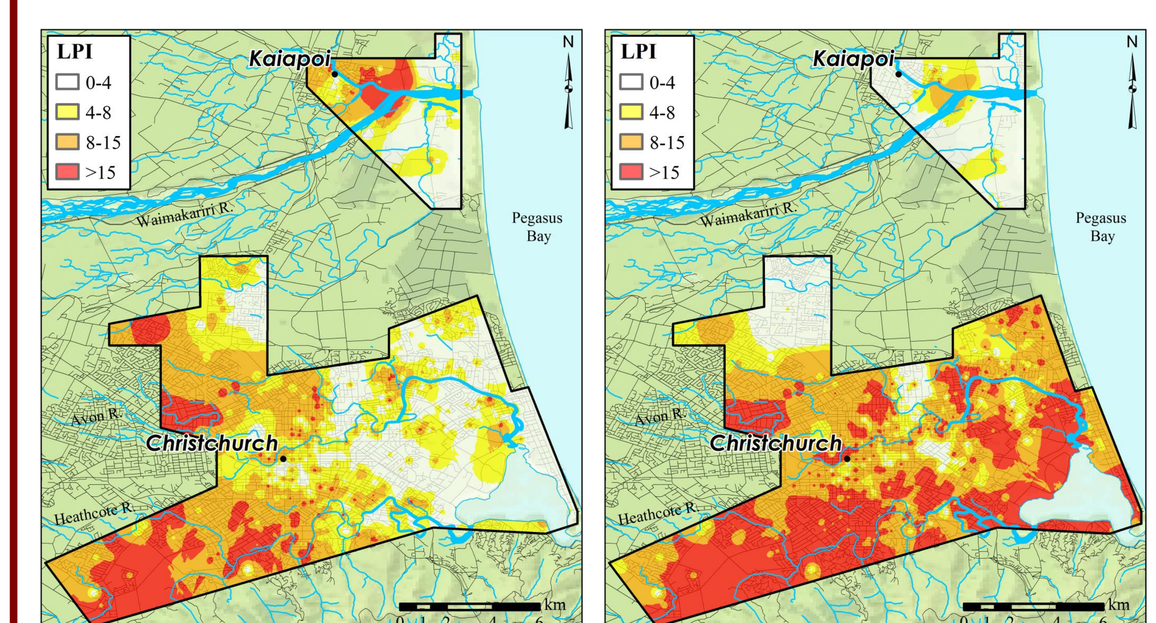

Fig 7. Liquefaction potential Index (LPI) during the (a) Darfield and (b) Christchurch earthquake

RESULTS AND DISCUSSION

1. Prediction of Liquefaction Occurrence (2346 Cases)

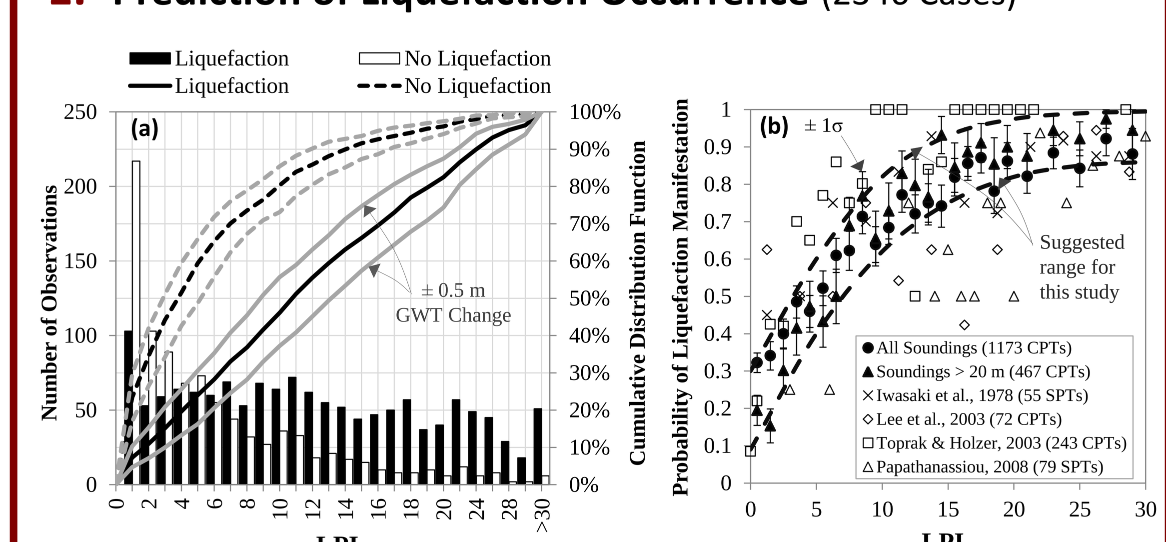

Fig 8. (a) Histograms and CDFs for CPT sites with and without liquefaction manifestation; (b) Probability of liquefaction manifestation for given LPI

- Using a threshold LPI value of 5, 24% of liquefied sites and 41% of non-liquefied sites are misclassified.
- A risk-based assessment may be of greater value than threshold LPI values; based on this study, the probability of liquefaction manifestation at sites with LPI values of 5, 10, and 15 ranges from 0.40 - 0.60, 0.62 - 0.82, and 0.75 - 0.93, respectively.

2. Prediction of Liquefaction Severity (2346 Cases)

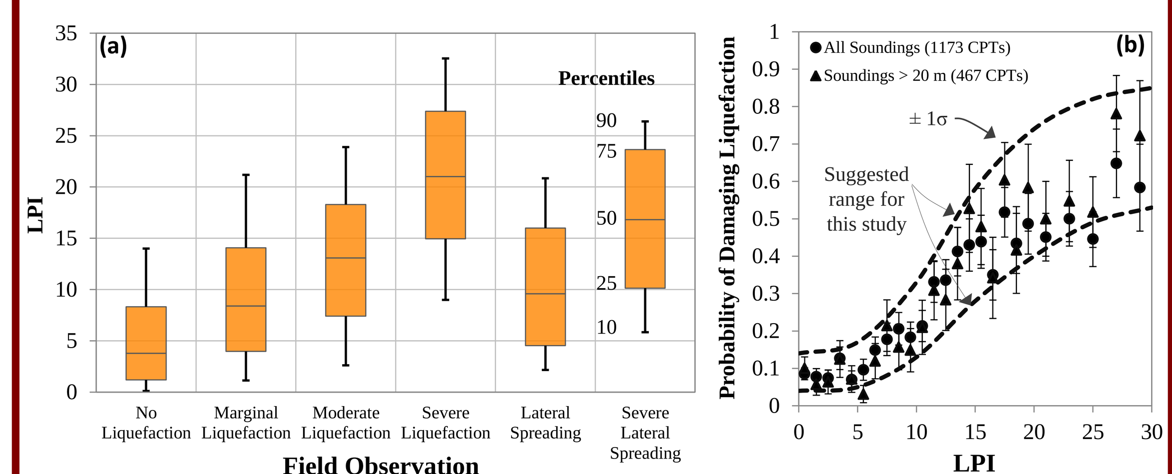

Fig 9. (a) Correlation between LPI and manifestation severity; (b) Probability of damaging liquefaction, where marginal manifestations are considered non-damaging

- The severity of manifestation generally increases with increasing LPI; the medians for marginal, moderate, and severe liquefaction are 8.4, 13.1, and 21.0, respectively.
- Lateral spreading possible at low LPI values; must consider influence of local conditions on the manifestation of liquefaction.
- Damage to infrastructure is more likely to result from moderate or severe liquefaction; the probability of damaging liquefaction at LPI = 5 ranges from 0.05–0.17.
- Thus, the *Iwasaki criterion* is more applicable for assessing the damage potential, rather than occurrence of liquefaction.

3. Spatial Analysis of LPI Performance

- LPI generally effective, but occurrence or severity of liquefaction was inaccurately predicted for a non-trivial percentage of sites; these sites were generally located in the southern margins of Christchurch:

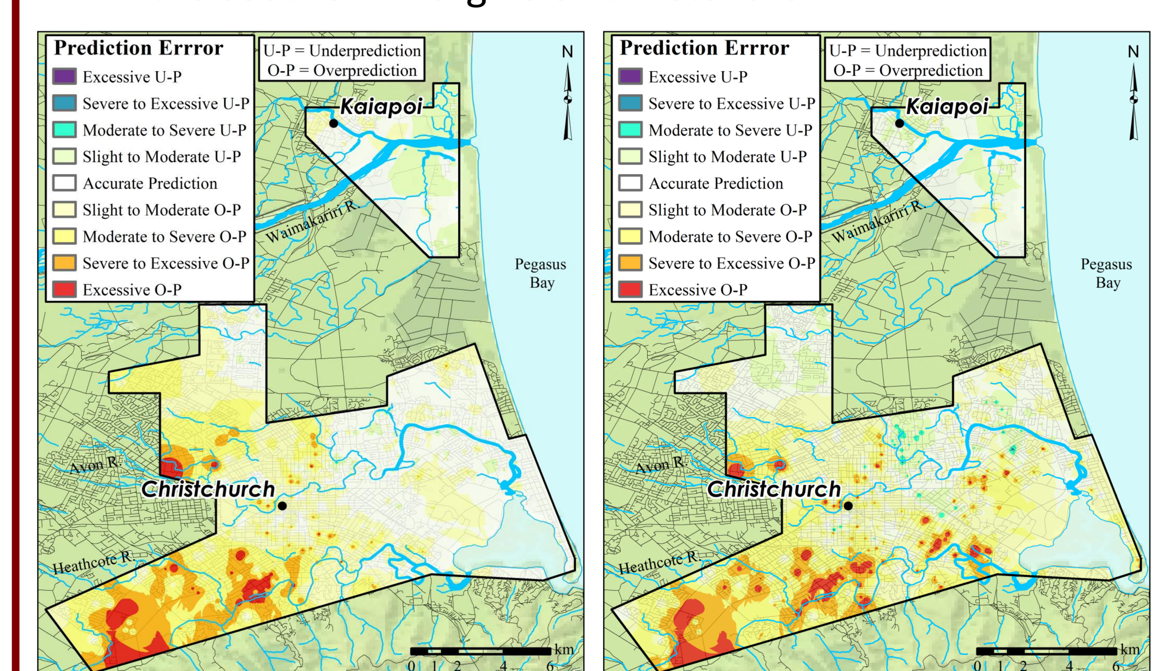

Fig 10. Liquefaction severity prediction errors for the (a) Darfield and (b) Christchurch earthquake

- Ground-water fluctuation and uncertainty of PGAs were among factors resolved to be unlikely cause of errors.
- Trend identified between liquefaction over-predictions and plasticity of soil in capping and/or interbedded non-liquefied layers; further research is needed to better understand and quantify these effects.

CONCLUSIONS

1. LPI and *Iwasaki criterion* generally effective in predicting damaging liquefaction; should be used with caution in locations susceptible to lateral spreading.
2. Liquefaction probability better than threshold LPI values.
3. LPI could be improved by accounting for characteristics of soils in both layers predicted to liquefy and the crust and/or interbedded layers predicted not to liquefy.